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Effectiveness of Fire Extinguishing Powders Based on Small Scale Suppression Tests

GUNTHER FISCHER

Wehrwissenshaftliche Dienstelle der Bundeswehr fur ABC-Schutz

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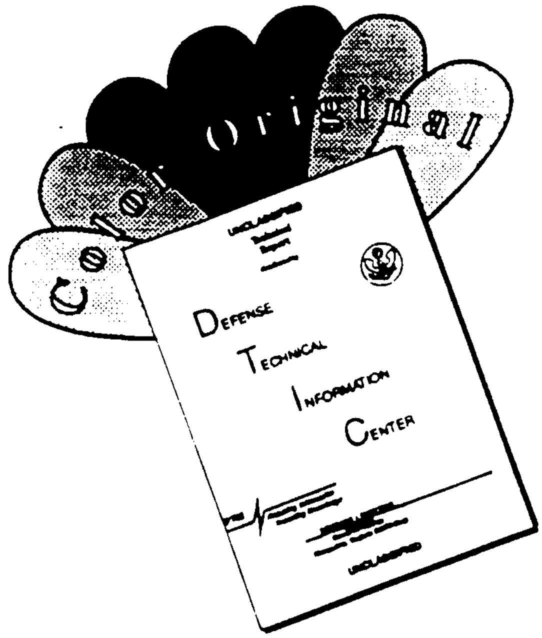

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A simple laboratory test method was developed for evaluating the fire extinguishing power of dry chemical agents. The apparatus consisted of a Bunsen burner which was modified by the addition of a delivery tube to permit the dry chemical powder to be injected into the methane/air stream about 4 cm below the burner tip. The powder concentration was increased until the test flame was extinguished. A total of 21 commercial extinguishing powders were tested in this apparatus. It was found that the fire extinguishing effectiveness of a given powder is primarily determined by its particle size rather than its chemical composition. For four of the agents tested ($KHCO_3$,$NH_4H_2PO_4$, KCl and $NaHCO_3$), it was found that the fire extinguishing performance could be divided into three regions: 1) a very effective range up to 25 μm, 2) a transition range with a steep effectiveness slope in the 25-50 μm particle size range, and 3) relatively ineffective range above 50 μm. The same type of behavior was found for Monnex™ except that very effective range extended to about 40 μm and the transition range was 40-60 μm.

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TABLE OF CONTENTS

EFFECTIVENESS OF FIRE EXTINGUISHING POWDERS BASED ON SMALL SCALE FIRE SUPPRESSANT TESTS

Introduction

It is very difficult and costly to test the effectiveness of extinguishing powders against large fires. The test results may be influenced by weather conditions, method of agent application and operator technique. In addition, these tests require considerable amounts of fuel and extinguishing agent causing environmental pollution. Another problem may be obtaining a sufficient quantity of appropriate particle size fractions of a given extinguishing powder. Generally, the fractions are obtained by means of standard laboratory sieves in which case it is a slow and laborious process to accumulate sufficient quantities of a given particle size for a large scale fire test.

In view of the aforementioned reasons, it would be convenient to have a laboratory test device requiring only small amounts of samples for comparison tests of extinguishing powders. In fact, a number of such devices are described in the literature, e.g., W. Hoffmann describes as many as seven different types of apparatus in addition to proposing a new advanced apparatus [1,2]. Another approach is the Chamber Test Method developed by C. Ewing [3]. E.L. Knuth, et al. and C. Seeger used opposing jet burners for their studies [4].

The above methods can be divided into two groups: one using a premixed and the other a diffusion flame. They may further be classified as test methods simulating processes in an actual fire or as those providing ideal test conditions. To study the basic characteristics of an extinguishing powder, a test method should be used which ensures that all particles of the sample actually reach the flame. Practically, this requirement can be met only if the powder sample is carried into the test flame together with the air-gas mixture, as described in the present test method.

Experimental Procedure

Apparatus for Studying the Effectiveness of Dry Chemicals as Fire Extinguishing Agents

To test the fire extinguishing effectiveness of dry chemicals, a simple laboratory test method was developed using an apparatus (Figure 1) that operates in accordance with the Bunsen burner principle, and is provided with a powder delivery device on the burner tube side thus allowing a controlled supply of agent, air and fuel gas to enter the burner.

The tests were carried out with a micro burner having connections for pressurized air and methane. Gas supply was controlled by means of a rotameter. Methane was taken from a gas bottle and supplied via a reduction valve. Pressurized air was added from the house supply.

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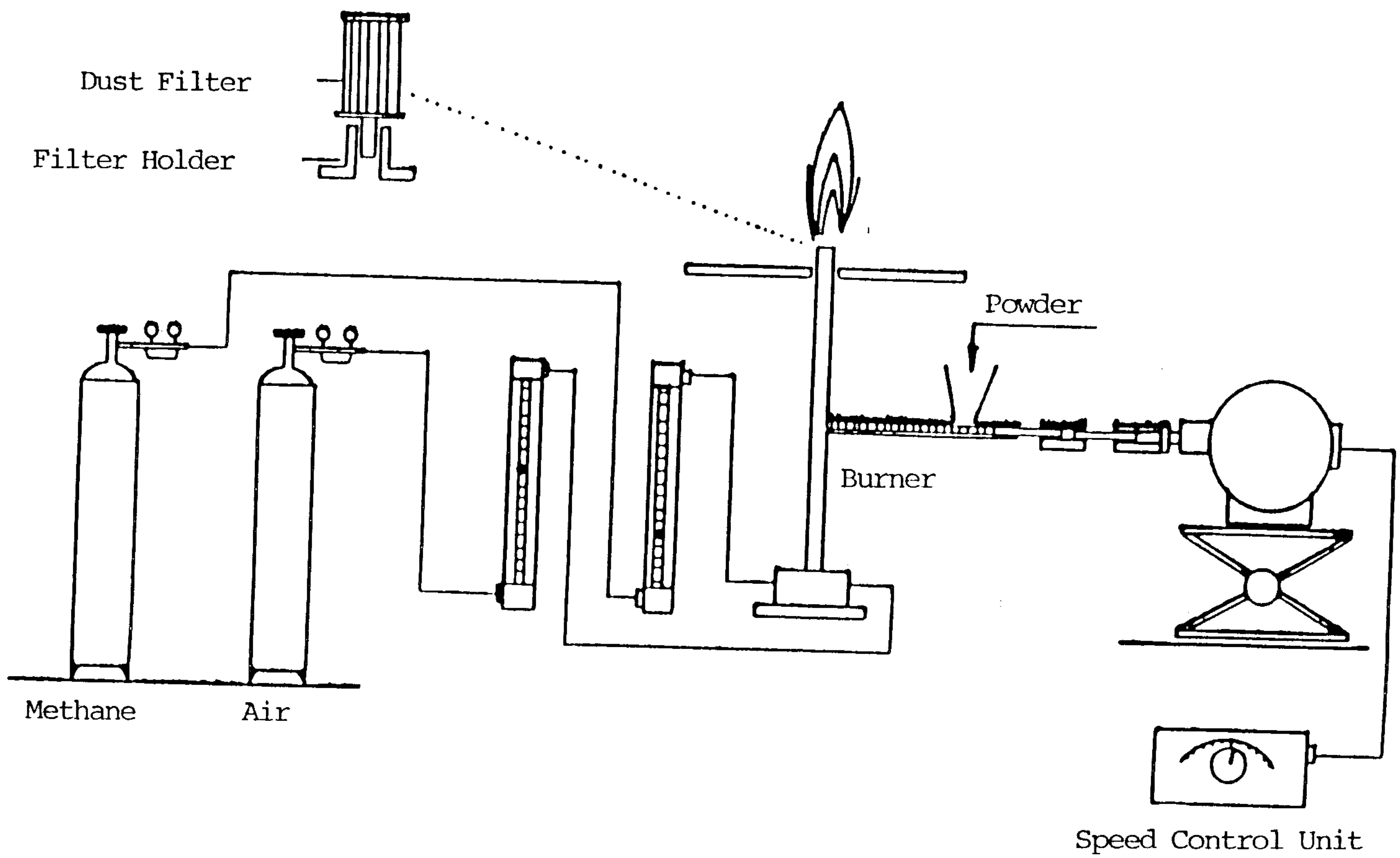

Figure 1. Small scale apparatus for measuring extinguishing power of dry chemical agents

The micro burner was provided with a 190 mm long glass tube having an inner diameter of 10 mm. Another 90 mm long tube was attached to the center of this tube at an angle of 90°. The side tube was provided with a small funnel which served as a powder reservoir. A specially designed feeder worm was connected to a drive motor by means of a slip clutch consisting of interlocking polyethylene hoses. The drive motor speed was controllable from 0 through 500 rpm.

The powder sample was supplied to the burner tube by means of the feeder worm. The burner tube also served as a mixing chamber. By controlling the gas flow it was ensured that all particles, even the large ones, were carried into the test flame. The apparatus is similar to one used by Thorne [5], except that the latter used a downward-pointing flame and had no filter for collecting the powder.

Preliminary tests indicated that a stoichiometric gas mixture did not provide the desired sensitivity, so a methane-enriched flame was used. During all tests, flow rates of 8.5 l/min for air and 1.35 l/min for methane were used resulting in a total gas mixture volume of 9.85 l/min and a methane concentration of 13.7%. The methane concentration was verified with a gas chromatograph.

The advantages of this test setup are:

- Simple operation
- Minor engineering effort
- Quick disassembly of burner and powder feeder for cleaning
- Only small amounts of powder (in the range of grams) are required for these tests. This is important for research and development as only small amounts of powder are available when working with common test sieves.
- With each individual sample a great number of individual measurements can be made at a relatively high rate. This is of particular importance with this type of test since it is considered necessary to conduct 5 to 10 individual tests for each datum point.

Measurement

The extinguishing powder sample is placed into the funnel and transported to the burner tube by means of the feeder worm. In the burner tube, the powder particles are mixed with the air-methane mixture and carried into the test flame by the flowing gas. The powder concentration in the air-methane mixture is increased by increasing the feeder worm speed until the test flame is extinguished.

If the powder samples have poor flow properties and do not move smoothly through the funnel, a mini-vibrator can be attached to the glass tube next to the funnel to ensure uniform powder flow.

Either the minimum powder flow rate, R (mg/min), or powder concentration, C_E (mg/ℓ of methane-air mixture) leading to flame extinction may be taken as a measure for the extinguishing effectiveness of the respective powder.

When testing individual particle size fractions, it is convenient to use the reciprocal of the determined minimum powder rate 1/R in min/mg for purposes of comparison, as described later. The required powder amount per unit time is determined by attaching a low-drag fine dust filter to the burner tube after the test flame has been extinguished. The weight gain of the filter is determined, and referred to the period of one minute. Normally, ten measurements were conducted per sample and the mean determined thereof.

The powder concentration required for flame extinction (C_E) is obtained by dividing the determined weight gain of the filter per minute by the flow rate of gas-air mixture in liters per minute.

It is necessary to thoroughly dry the powder samples in a desiccator prior to test since the slightest rise of moisture constant would bias the test results. With rising moisture content, the extinguishing effectiveness decreases due to caking of fine particles.

In order to obtain a comprehensive view of the effectiveness of extinguishing powders, a total of 21 commercially available powders from the United States and Germany were tested. The samples included:

8 based on monoammonium phosphate ($NH_4H_2PO_4$)
1 mixture of $NH_4H_2PO_4$ and ammonium sulfate [$(NH_4)_2SO_4$],
4 based on sodium bicarbonate ($NaHCO_3$)
3 based on potassium bicarbonate ($KHCO_3$)
1 based on potassium chloride (KCl)
1 on Monnex™ which is approximately 86% $KC_2N_2H_3O_3$
3 based on potassium sulfate (K_2SO_4).

These basic investigations were followed by tests carried out with five common extinguishing powders to determine the influence of particle size on extinguishing effectiveness. It is recognized, that particle size has a considerable influence on the extinguishing efficiency.

The individual particle size fractions were produced by means of a 3-D vibration sieve or an ultrasonic sieving device. The initial samples for the very fine particle size range were prepared by Donaldson Co., Inc. and Micromerities Instrument Corporation.

In a parallel effort, Ewing [3] used the same powder samples in his larger scale chamber test thus allowing a direct comparison of test results obtained with two different methods.

Results and Discussion

Commercial Powders

A comparison of the effectiveness of commercially available fire extinguishing powders from different U.S. and German manufacturers based on both the burner test and Ewing chamber test methods is given in Tables 1 and 2. These results are plotted in Figure 2.

Table 1. Minimum Extinguishing Rates for Commercial Fire Extinguishing Powders from the United States				
Sample Number	Major Constituent	Burner Test R(mg/min)	C_E(mg/ℓ)	Chamber Test g
1	$NH_4H_2PO_4$	140	14.2	72
2	"	104	10.6	47.2
3	"	92	9.3	54.7
4	"	120	12.2	--
5	"	98	9.9	51.3
6	"	102	10.4	51.2
7	"	147	14.9	73.9
8	"	71	7.2	41.2
9	$NaHCO_3$	118	12	47
10	"	123	12.5	54
11	$KHCO_3$	44.5	4.5	26.4
12	"	45	4.6	29
13	"	90	9.1	62
14	KCl	118	12	47
15	Monnex™	80	8.1	31.5

Table 2. Minimum Extinguishing Rates for Commercial Fire Extinguishing Powders from Germany				
Sample Number	Major Constituent	Burner Test R(mg/min)	C_E(mg/ℓ)	Chamber Test g
16	$NaHCO_3$	130	13.2	55
17	"	128	13	55
18	$NH_4H_2PO_4$/ $(NH_4)_2SO_4$	125	12.7	47
19	K_2SO_4	167	17	65
20	"	252	25.6	
21	"	250	25.4	

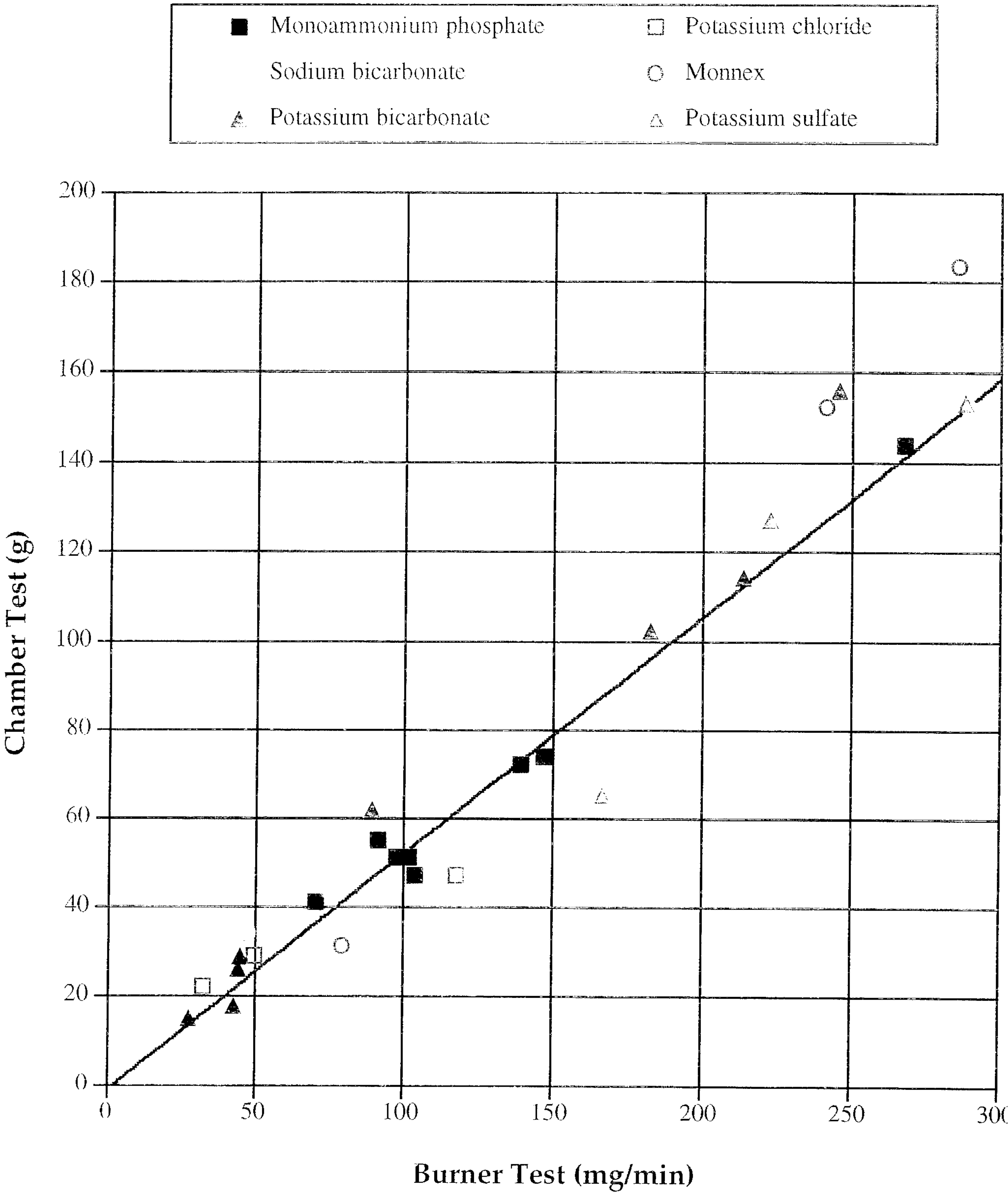

Figure 2. Correlation between small scale tests and Ewing's chamber tests [3]

It is apparent from the figure that commercial powders vary widely in their effectiveness as firefighting agents. For example, some of the lowest and some of the highest values were obtained for both potassium bicarbonate and Monnex™ indicating that chemical composition by itself, is no indicator of fire suppression performance. Rather, particle size of the extinguishing powder is the primary consideration.

From Figure 2, it can also be seen that the data obtained with the two completely different methods are in surprisingly good agreement. Earlier workers, such as W. Hoffmann [1], have noted that in many cases it is not possible to compare results obtained with different test apparatus since their different experimental conditions considerably influence the test results.

Effect of Particle Size on Extinguishment

The commercial powder comparison tests were followed by tests to determine the influence of particle size on effectiveness. For these tests the five most common extinguishing powders were used, namely, agents based on monoammonium phosphate, sodium bicarbonate, potassium bicarbonate and potassium chloride as well as Monnex™. The results of these tests are given in Tables 3-7. It was found that there is a direct relation between particle size and effectiveness of extinguishing power for all powders tested. If the minimum rate, R, required to extinguish the test flame is plotted as a function of particle size, the curves obtained are similar to the titration curves produced in analytical chemistry (Figures 3-7).

If the reciprocal of minimum rate, R, is defined as effectiveness, E, and if E is plotted as a function of particle size, the curves obtained for the five extinguishing powders are remarkedly similar to each other (Figure 8). The figure also shows that, except for Monnex™, the effect of chemical composition of the agent doesn't become significant until the particle size is less than 25 μm. Monnex™ continues to show higher effectiveness than the other powders in the particle size range of 20-60 μm. The reason for this becomes clear if one assumes, as suggested by the manufacturer, that the Monnex™ grains disintegrate into smaller particles in the flame.

In general, the effectiveness of the extinguishing powders can be subdivided into three ranges, namely, a very effective range with particles <25 μm, a transition range (particles 25-50 μm) with a steep effectiveness slope and a third relatively ineffective range with particles >50 μm - see Figure 8. This also applies to Monnex™ with all three ranges shifted to the right by approximately 15 μm. With Monnex™ the effective range goes up to approximately 40 μm and the relatively ineffective range begins at approximately 65 μm.

It is also apparent from Figure 8 that the really significant differences among the extinguishing powders tested result from powder behavior in the range of particles <25 μm. In other words for a given powder, the higher the percentage of low particle size material it contains, the more effective the agent will be. The differences in the range of particles >25μm, as evident from Figures 3 through 7, have only a minor influence on the effectiveness of a formulated extinguishing powder mixture. It also becomes clear that there is no linear relationship between effectiveness and particle size, but rather there are three ranges in effectiveness which deviate considerably from each other.

Table 3. Minimum Extinguishing Rates for a Monoammonium Phosphate Fire Extinguishing Powder (Sample 3) as a Function of Particle Size		
Particle Size µm	**Burner Test R mg/min**	**C_E mg/ℓ**
1-10	33	3.4
10	36	3.7
≤37	36	3.7
≤44	43	4.4
≤62	63	6.4
37-44	196[1]	19.9
44-62	266[1]	27.0
62-105	286	29.0
≤105	306	31.1

[1] These powder samples were found by screen analysis to contain significant weight fractions of particles below 30 µm; the results reported are for clean samples and corrections were made using the mixture relationship reported in [3].

Table 4. Minimum Extinguishing Rates for a Sodium Bicarbonate Fire Extinguishing Powder (Sample 9) as a Function of Particle Size		
Particle Size µm	**Burner Test R mg/min**	**C_E mg/ℓ**
4	42	4.3
7	45	4.6
≤37	48	4.9
37-41	283[2]	28.8
44-53	290	29.4
62-75	312	31.7
88-87	316	32.1
105-127	312	31.7

[2] This powder sample was found by screen analysis to contain a significant weight fraction of particles below 15 µm; the result is for a clean sample and correction was made using the mixture relationship reported in [3].

Table 5. Minimum Extinguishing Rates for a Potassium Bicarbonate Fire Extinguishing Powder (Sample 11) as a Function of Particle Size

Particle Size µm	Burner Test R mg/min	C_E mg/ℓ
6	35	3.6
≤ 37	42	4.3
37-44	112[3]	11.4
44-62	184	18.7
62-74	214	21.7
74-88	226	22.9
88-105	240	24.4
≥ 105	273	27.7

[3] A screen analyis on this sample was not made; but, based on the small particle-size contaminations found in similar samples for sodium bicarbonte and monoammonium phosphate, the reported results I believed to be low.

Table 6. Minimum Extinguishing Rates for a Monnex[4] Fire Extinguishing Powder (Sample 15) as a Function of Particle Size

Particle Size µm	Burner Test R mg/min	C_E mg/ℓ
≤ 37	38	3.9
≤ 44	39	4.0
44-62	89	9.0
44-62	184	18.7
62-74	243	24.7
74-88	--	--
88-105	338	34.3
105-125	406	41.2
125-149	423	42.9
≥ 149	~ 550	55.8

[4] Purchased from ICI Americas, Inc.

Table 7. Minimum Extinguishing Rates for a Potassium Chloride Fire Extinguishing Powder (Sample 14) as a Function of Particle Size

Particle Size µm	Burner Test R mg/min	C_E mg/ℓ
2-20	39.5	4.0
≤ 37	49	5.0
44-62	248	25.2
62-88	235	23.9
88-105	200	20.3

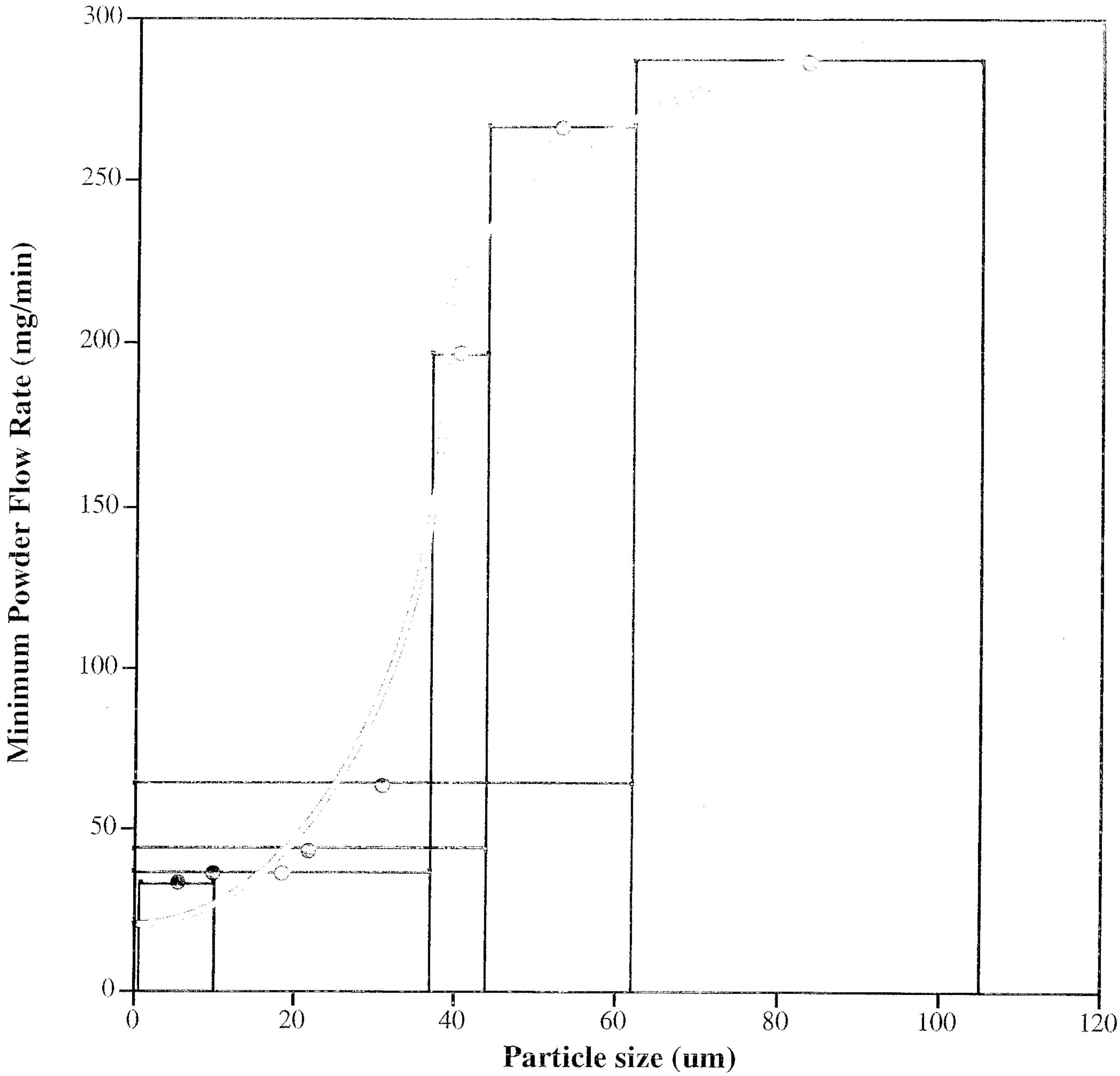

Figure 3. Effect of particle size of monoammonium phosphate on minimum powder flow rate for extinguishment

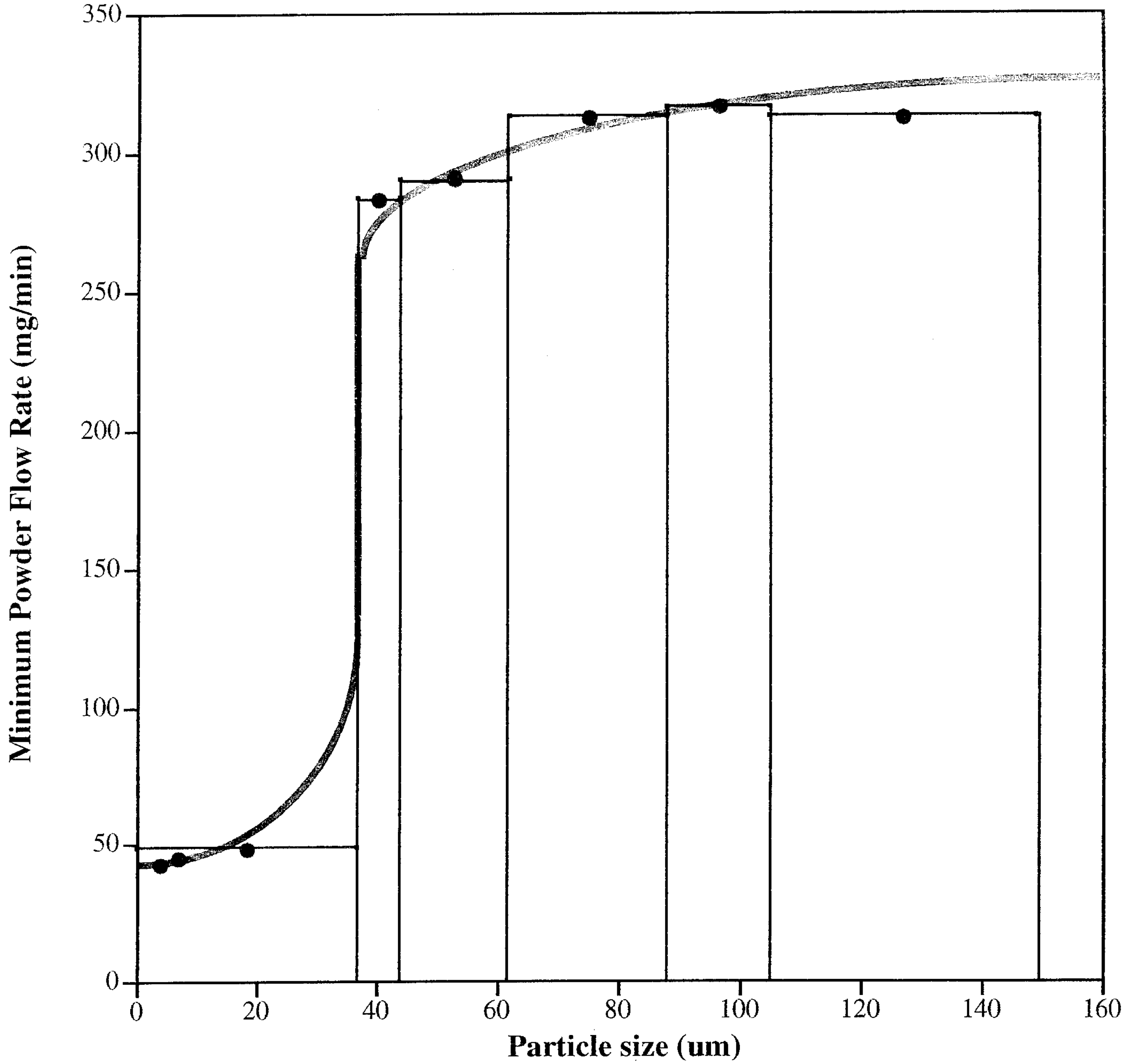

Figure 4. Effect of particle size of sodium bicarbonate on minimum powder flow rate for extinguishment

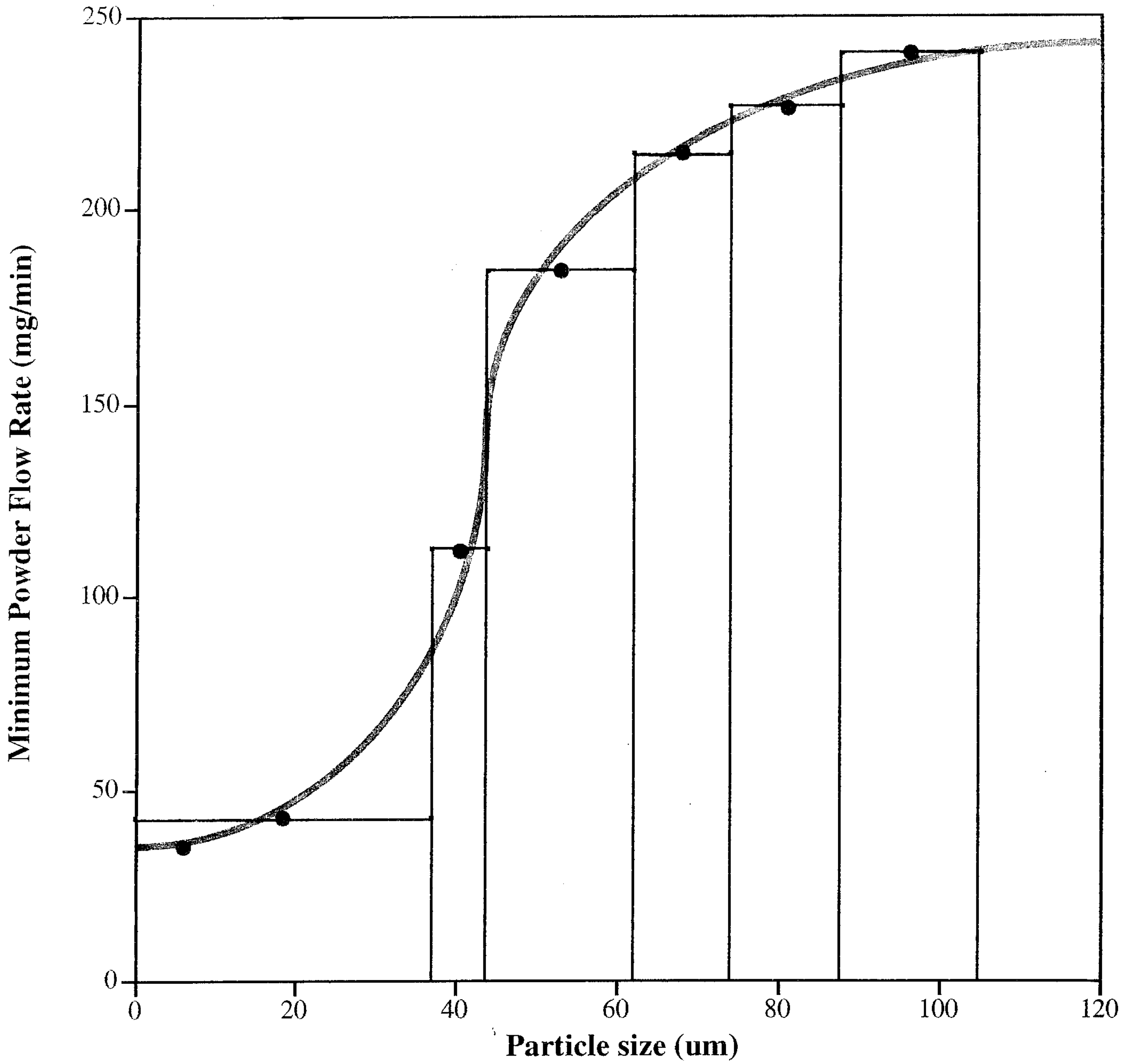

Figure 5. Effect of particle size of potassium bicarbonate on minimum powder flow rate for extinguishment

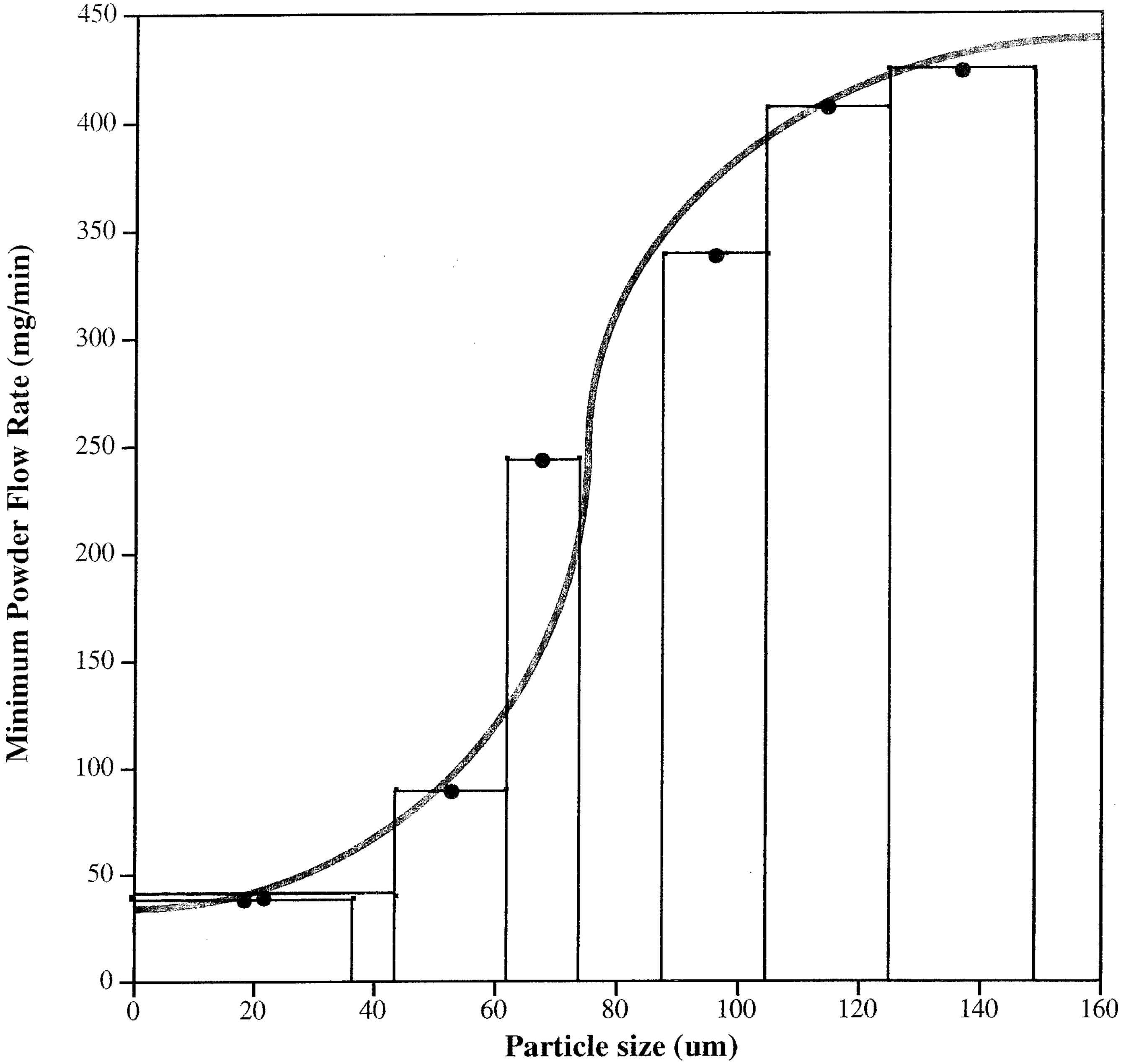

Figure 6. Effect of particle size of Monnex™ on minimum powder flow rate for extinguishment

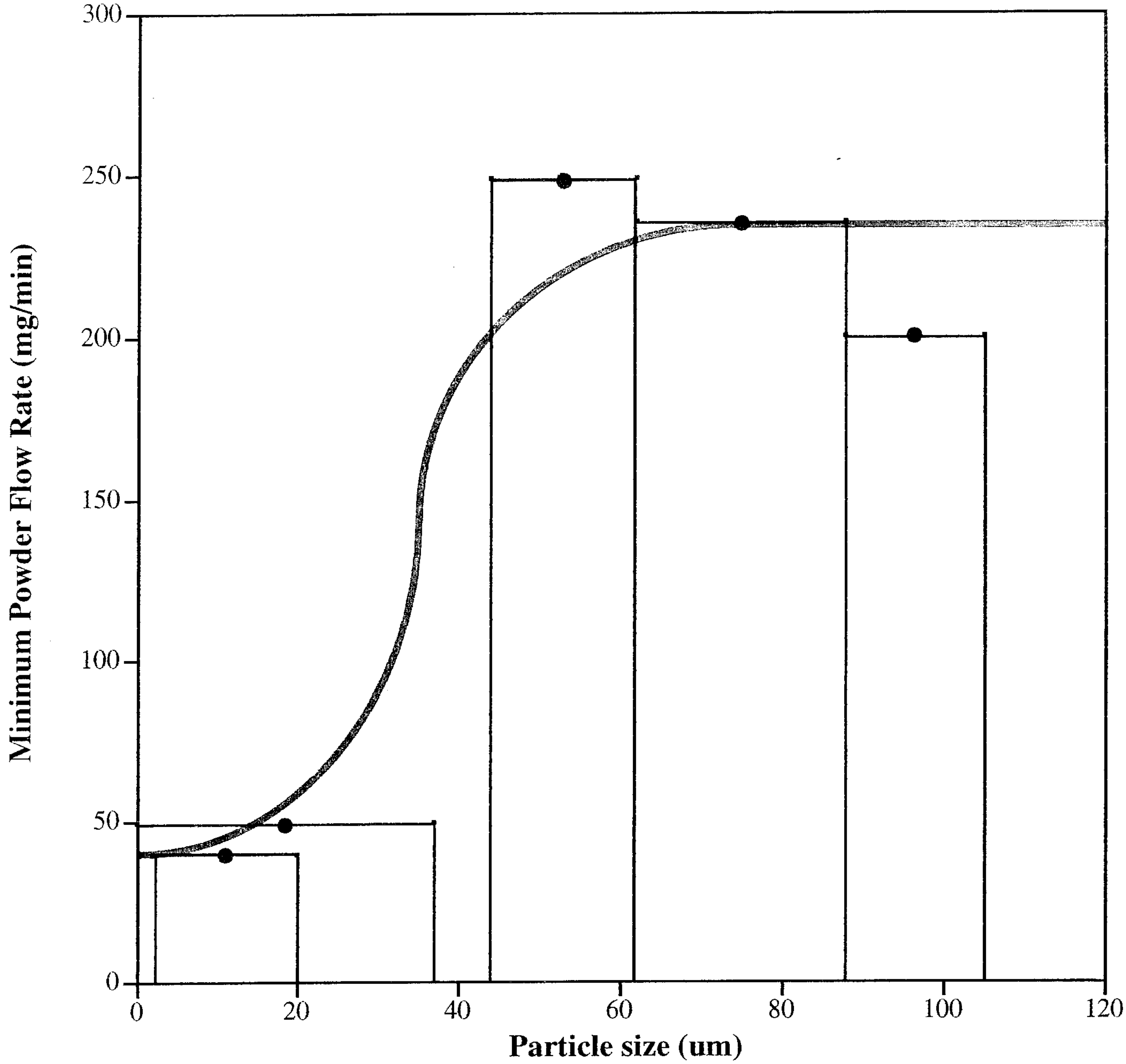

Figure 7. Effect of particle size of potassium chloride on minimum powder flow rate for extinguishment

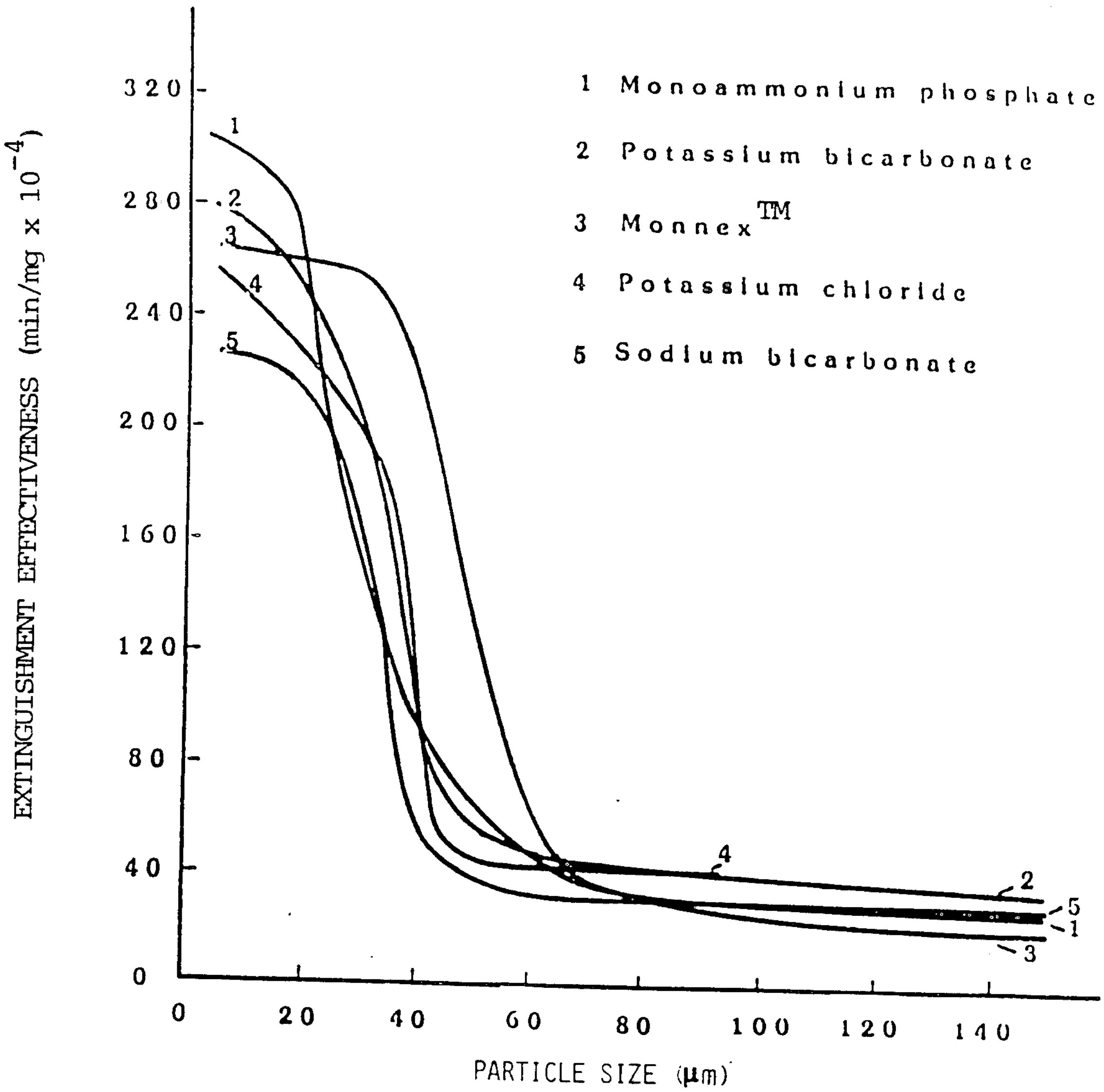

Figure 8. Effectiveness of various extinguishing powders as a function of particle size

Figure 9 shows particle distributions of the five extinguishing powders tested. While sodium bicarbonate and potassium bicarbonate have similar particle distributions, the curves of the other extinguishing powders are considerably different from each other. The portions of fine particles ≤ 25 µm are relatively uniform for potassium bicarbonate, sodium bicarbonate and potassium chloride ranging from 50% through 60%. In contrast, monoammonium phosphate has a fine particle fraction of only approximately 30%.

The curves in Figure 8 show that Monnex™ is a very effective extinguishing agent, particularly in the particle size range of 25 to 60 µm. The reason for the high effectiveness is, of course, that the Monnex™ particles decrepitate or breakup in the flame producing a number of smaller particles. If each Monnex™ particle in this range merely broke in half, it would double the number of particles of Monnex™ in the very effective <25 µm range which, in effect, would shift the curve for Monnex™ in Figure 8 to the left bringing it more in line with the curves for the other agents. The data in Figure 6 support this conclusion showing that the commercial Monnex™ powder is a far better extinguishing agent than one would expect based on the particle size distribution in Figure 9. Very similarly-shaped curves were found by Ewing, et al. (3) for suppression of heptane pan fires using the same agents but a much larger and quite different apparatus - Figure 10.

Application to Firefighting

In his report, "Fire Prevention - Fire Extinguishing," K. Raffalsky [6] states that during laboratory tests carried out with potassium salts, only 25% of the actual effectiveness was achieved when applied to "hot objects." Previously, it was not possible to explain this phenomenon. However, the findings from the present tests now provide the basis for an explanation. Testing only a limited particle size range of a given agent as is done quite often, could lead to a misleading evaluation of the extinguishing effectiveness of a particular chemical agent, as would be a comparison of commercial products having identical chemical compositions, but, very different particle size distributions. This, undoubtedly, is what led earlier workers to conclude that potassium bicarbonate is twice as effective as a firefighting agent as sodium bicarbonate [7]. The results of this investigation indicate that just the opposite conclusion could be reached if one chose the proper particle size ranges for the comparison.

If one further considers that from a technical point of view there are no significant differences in the extinguishing effectiveness of common powders above 25 µm (the only exception is Monnex™), and that the portion of fine particles <25 µm is the determining factor for the total extinguishing power of a powder mixture, and, if one also bears in mind that only a fraction of the very fine particles is carried into the flame during application (the rest is blown away by wind and flame lift), it becomes clear that the reputed differences between the extinguishing powders in question will diminish if suitable application methods are not used.

The differences due to chemical composition become clear only if an application method is used which ensures that even the small particles become effective to a large extent. Hence, the effectiveness of an extinguishing powder is also determined by the type of application.

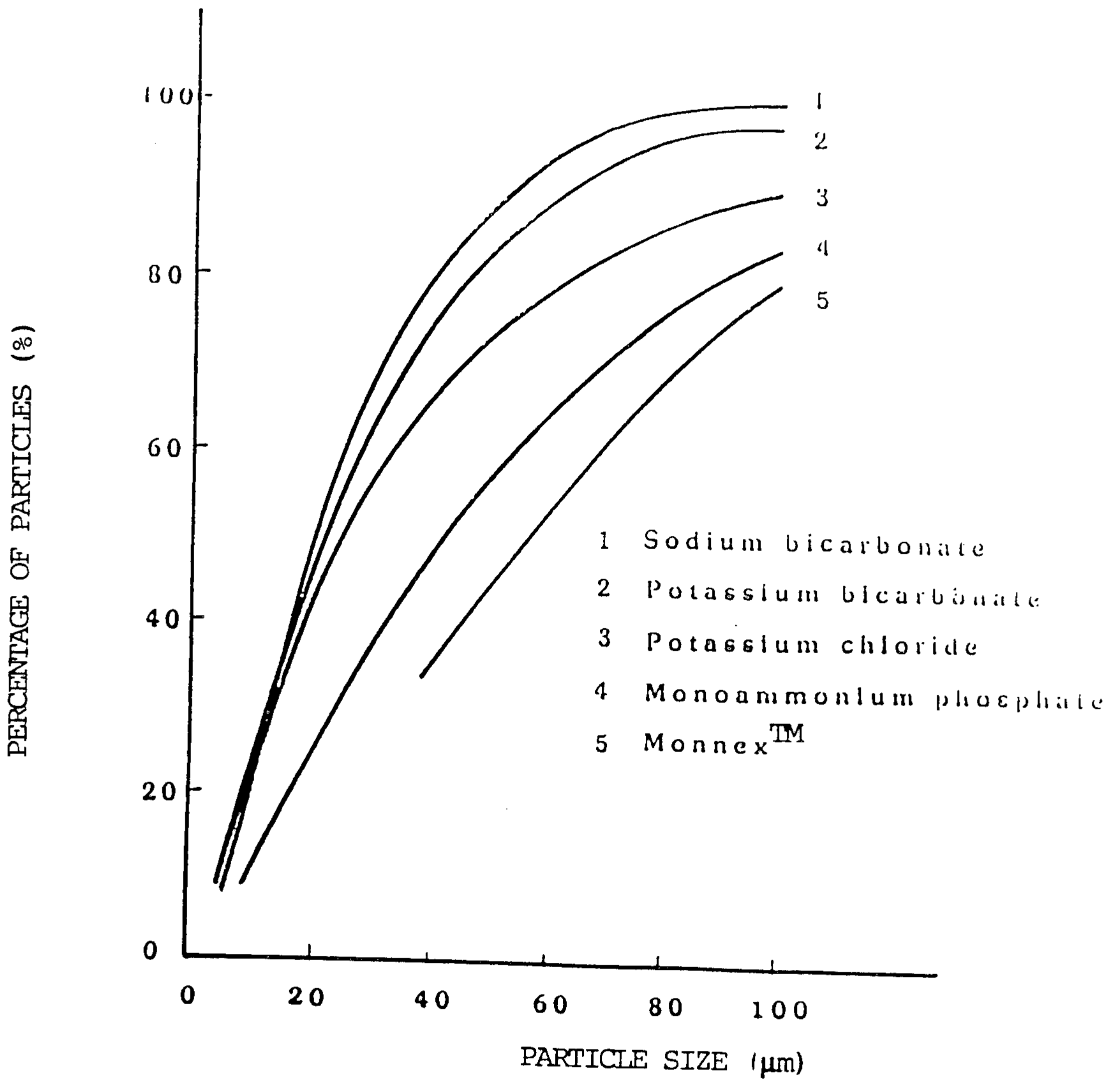

Figure 9. Particle size distributions for various commercial extinguishing powders

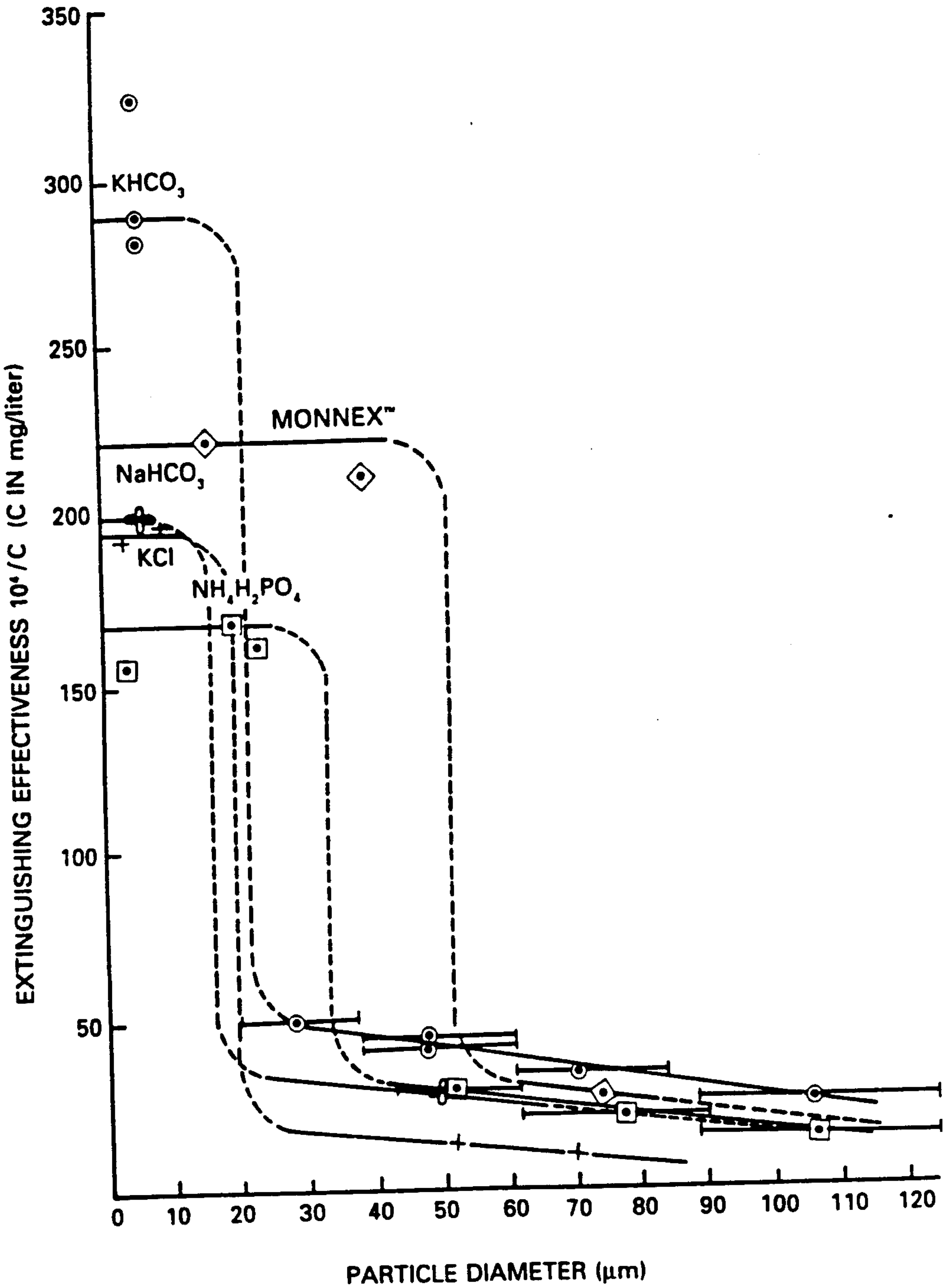

Figure 10. Effectiveness of dry chemical agents as reported by Ewing [3]

It appears that the effectiveness of extinguishing powder can only be increased by:

- Optimizing the application equipment
- Optimizing the application techniques
- Searching for chemicals which disintegrate into small particles in the flame (A start has been made with Monnex™)
- Searching for method to carry small particles over long distances into the flame, to take advantage of the enhanced extinguishing power of small particles

Summary and Conclusions

To test the effectiveness of extinguishing powders, a simple laboratory test method was developed using an apparatus which continuously feeds powder into a methane/air stream. The resulting powder and fuel/air mixture is carried directly into the test flame. The powder concentration is increased until the test flame is extinguished and then the powder application rate is measured in mg/min. With this procedure, it is possible to test extinguishing powders of different chemical compositions.

Investigations of 21 U.S. and German commercial extinguishing powders showed that the fire extinguishing effectiveness of a given powder is primarily determined by the particle size of the powder rather than by its chemical composition. This was true for all of the powders tested except Monnex™ which decrepitates in a flame giving a higher percentage of small particle size material than was present in the original agent.

For four of the five extinguishing powders investigated, a characteristic curve was found showing extinguishing effectiveness as a function of particle size. This characteristic curve applies to particle sizes above 25 µm.

Agents disintegrating into small particles in the flame, e.g., Monnex™, display a similar characteristic curve, but the curve is shifted toward large particle sizes.

The following three particle size ranges were found:

- Very effective range up to approximately 25 µm
- Transition range with a steep effectiveness slope (25-50 µm)
- Relatively ineffective range above 50 µm

From the test results it is concluded that, except for Monnex™, the differences between the commercial products are mainly due to the percentage of small particles ($\leq$ 25 µm) present in the sample. Above 25 µm, all extinguishing powders investigated behave similarly, regardless of their composition. Chemical composition seems to be relevant only in the range of particles below 25 µm.

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